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Effects of forest policy on landscape pattern of late-seral forest of the Western Olympic Peninsula, Washington

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Abstract

Forest harvest policies and regulations in the Pacific Northwest region of the United States have changed considerably across all land ownerships over the last 25 years, primarily in response to concerns over threatened and endangered species. For example, in July 2001, Washington State adopted new forest practice rules for private ownerships, which were aimed primarily at improving habitat for aquatic and riparian species. Before adopting the new rules, an environmental impact assessment was conducted in which three alternatives were considered in detail for their contributions to riparian habitat. Implications for upland species were not considered, although riparian protection has the potential to make contributions to habitat for obligate late-seral species.

Effects of the three management alternatives were projected on private lands 200 years into the future, holding constant current practices on other lands managed for timber (federal, tribal, and state). The resulting distribution of late-seral forest across the Western Olympic Peninsula was compared. Simulations predicted that late-seral forest would cover between 39 and 48% of the landscape, well above the 8% that it currently occupies. Five to 21% of this late-seral forest would be on private lands (compared to <1% currently), and 71–85% on public lands (compared to 91% currently). Landscape pattern analysis indicated that the total amount of late-seral forest was significantly different among the three scenarios. However, there was no discernible difference in interior forest area, edge density, and mean distance between patches between a "no-action" alternative and the alternative that was ultimately adopted into rule. The most protective alternative had significantly more interior forest area and greater mean distance between patches, but it also had significantly higher edge density as a result of the linear nature of the riparian reserves and small patches of steep, unstable slopes. Our analysis framework will be useful for evaluating the effects of alternative management scenarios on landscape pattern across broad geographic areas with complex ownership.

Keywords: Landscape pattern; Fragmentation; Forest policy; Late-seral forest; Olympic Peninsula; Washington

1. Introduction

Loss and fragmentation of late-seral forest ecosystems have generated concern for species that are sensitive to disturbance or require late-seral forest habitat (Thomas et al., 1990, 1993; FEMAT, 1993; Jules, 1998). The dispersed, short-rotation forest practices of the second half of the 20th century have left late-seral forests of the Pacific coastal region of North America greatly reduced in spatial extent and highly fragmented (Garman et al., 1999) (Fig. 1). It will take considerable time to modify this legacy of landscape pattern (Franklin and Forman, 1987; Wallin et al., 1994).

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Fig. 1. Landscape pattern of the Olympic National Park and adjacent timber-managed lands. Photo used with permission of LightHawk.

Landscape structure is known to affect forest herb recruitment (Jules, 1998; Scheller and Mladenoff, 2002), species richness and abundance of plants (Jacquemyn et al., 2001) and animals (Andrén, 1994; Walters et al., 1999), nest parasitism and nest predation (Marzluff and Restani, 1999), and other ecosystem processes (Gustafson and Parker, 1992). Marzluff and Ewing (2001) suggest that the ecological severity of fragmentation is determined by historic disturbance regime, degree of similarity between the natural matrix and anthropogenic matrix, and persistence of the cause of fragmentation (e.g., timber management versus urbanization). Fragmentation has been given many definitions. Its use here will refer to subdivision of a specified habitat type, in this case late-seral forest, usually associated with decreasing patch size, increasing edge density and increasing distance between patches.

Descriptive measures of landscape structure are an important tool for evaluating habitat conditions and can be useful in comparing alternative scenarios of land management (Ripple et al., 1991; Gustafson and Parker, 1992). Landscape pattern indices have been used to compare dispersed and aggregated cutting patterns (Wallin et al., 1994) and anthropogenic and natural disturbance regimes (Cissel et al., 1999), predict historical extent of late-seral forest (Wimberly et al., 2000), and evaluate the role of land ownership in affecting landscape pattern (Turner et al., 1996; Pearson et al., 1999).

Washington State recently adopted new forest practice rules for private lands that address concerns about declining anadromous fish populations and water quality (WFPB, 2001a). Three alternatives were considered in detail in the environmental impact statement (EIS) prepared prior to adopting the permanent Washington Forest Practice Rules (WFPB, 2001b). The EIS evaluated effects on riparian and aquatic habitats for each alternative, but did not predict distribution of late-seral habitat through landscape pattern analysis, even though the reserves required by the alternatives have the potential to affect interior forest species that are also regulated in Washington Forest Practice Rules (marbled murrelet, *Brachyramphus marmoratus* and northern spotted owl, *Strix occidentalis caurina*).

Landscape structure resulting from these regulations will be affected by complex land use and ownership patterns. Since 1900, the predominant land use on low-elevation forest land of the Olympic Peninsula has been timber production. Multiple ownerships are tightly interspersed. Different forest practice regulations exist for federal, tribal, state, and private land owners. In most cases, these regulations were developed without consideration of the effects of management practices of other land owners on landscape pattern, even though the cumulative effects of past forest management practices have contributed to deterioration of water quality and subsequent regulation under the Endangered Species Act and the Clean Water Act (WFPB, 2001a), which regulate all land owners.

The three scenarios considered in the EIS for private lands in Washington State (WFPB, 2001a) are projected and the extent and distribution of late-seral forest over multiple ownerships are quantified. Timber management is simulated on each ownership, incorporating current (1999) parameters (harvest volumes, harvest unit size, etc.) and projected 200 years into the future. A suite of landscape pattern metrics are used to characterize the relative impacts of each alternative on the distribution of late-seral forest.

2. Methods

2.1. Study area

The Western Olympic Peninsula is located between the Pacific Ocean and the steep slopes of the Olympic Mountains in the northwest corner of Washington State. The study area (Fig. 2) is 274,692 ha in size and includes areas within the Bogachiel, Hoh, Clearwater, Queets, Quinault and Humptulips River drainages (124°27′W, 47°15′N–123°33′W, 47°54′N) that have been managed primarily for timber during the last 100 years. The focus of this study is on low-elevation forests; 1200 m was selected as an upper bound in each drainage.

The maritime climate is characterized by mild, wet winters (mean January temperature of 4 °C, Clearwater weather station, 1931–1999) and cool, dry summers (mean August temperature of 15 °C). Annual precipitation averages 306 cm (NCDC, 1931–1999) and falls primarily as rain; areas over 700 m elevation receive precipitation primarily as snow (Henderson et al., 1989). Summer fog is common at lower elevations

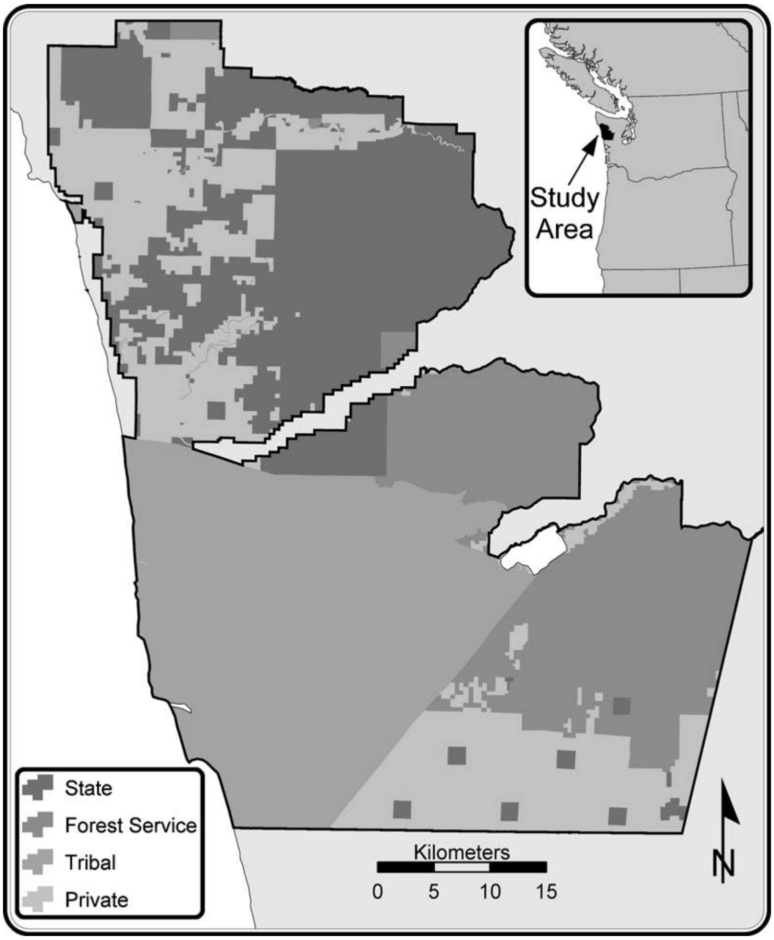

Fig. 2. Land ownership of the study area.

and is important in ameliorating moisture stress during the dry summer months.

Common low-elevation tree species, in order of the highest 1999 harvest volumes reported for the area (Larsen and Nguyen, 2001) include western hemlock (*Tsuga heterophylla*), Douglas-fir (*Pseudotsuga menziesii*), western redcedar (*Thuja plicata*), and Pacific silver fir (*Abies amabilis*). In late-seral forest, dominant trees of these species frequently had diameters of 150 cm or more (Tyler, 2002) and live biomass may exceed 1500 metric t/ha (Franklin and Spies, 1983).

Stand replacing natural disturbance events include episodes of high winds and infrequent (>250 years), high-severity fires (Henderson et al., 1989; Agee, 1993). A significant wind event occurred in 1921 and affected a 50 km wide strip for more than 250 km of coastline (Campbell, 1979). Fires over the last 700 years have occurred primarily on southerly aspects at mid-elevations and typically have covered less than 4 km^2 (Henderson et al., 1989). It may take 35–75 years for Douglas-fir to become established following intense fires (Huff, 1995).

2.2. History of ownership and land use

Ownership within the study area is comprised of the Quinault Indian Nation (30% of the study area), Olympic National Forest (21%), Washington Department of Natural Resources (26%), and private holdings, primarily by large timber companies (23%). The

Olympic National Park comprises the central core of the Olympic Peninsula and is adjacent to the study area. The park has remained largely undisturbed and thus is not included in this analysis of alternative forest management practices.

The current patterns of seral stage distribution have been developing since the onset of timber harvesting shortly after Euro-American settlement began in the mid-1800s. The first sawmill was established in 1850 (Campbell, 1979). Railroad logging in the 1920s and 1930s, in conjunction with the introduction of the logging truck in the late 1910s and completion of US Highway 101 in 1931, cleared some of the largest contiguous tracts on the Olympic Peninsula to date (Capoeman, 1991). In 1926, 6.9 billion board ft of timber were removed from western Washington (data provided by David Larsen, WDNR). A second peak of timber harvest occurred in the 1970s and 1980s; 6.6 billion board ft were harvested in western Washington in 1973 (Larsen and Nguyen, 2001). Coastal late-seral forests dominated by Sitka spruce (*Picea sitchensis*) have been nearly eliminated (Peterson et al., 1997). By 1988 late-seral forest on the Olympic National Forest had decreased by 76% from 1940 levels (Morrison, 1990). However, timber harvest on federal lands virtually ceased as a result of the Interagency Scientific Committee Report (Thomas et al., 1990) and implementation of the Northwest Forest Plan (USDA and USDI, 1994). Washington Department of Natural Resources lands continue to be logged, although annual harvest in the study area dropped from 405 ha in 1975 to 120 ha in 2000 (data provided by Liane White, WDNR). Harvest volume also declined on tribal and private ownerships in the 1990s, although the rate of decrease was less than that on state and federal lands (Larsen and Nguyen, 2001).

2.3. Forest practice regulations in Washington

Laws regulating forest practices vary by land owner. Private lands are regulated by Washington Forest Practice Rules, which were first adopted in 1976. The most recent Washington Forest Practice Rules revisions were adopted in July 2001 in response to declining fish stocks across Washington. These revisions were designed to provide compliance with the Endangered Species Act for aquatic and riparian species and meet the requirements of the Clean Water Act while maintaining a viable timber industry (WFPB, 2001a). To meet these goals, the new rules include greater protection of waterways and unstable slopes.

State lands were covered by the Washington Forest Practice Rules until Washington Department of Natural Resources developed Washington's Habitat Conservation Plan in 1997. As a sovereign state, the Quinault Indian Nation has its own Forest Practices Regulations (Quinault Indian Nation, 1979). Federal lands are governed by the Northwest Forest Plan. All land owners must comply with the Clean Water Act and Endangered Species Act.

2.4. Mapping current conditions

Current distributions of four forest-age categories were mapped: regeneration (0–19 years), young (20–79 years), mature (80–199 years), and late-seral (>200 years). These age categories were based on Oliver's stand development model (Oliver, 1981). The regeneration age category is comparable to Oliver's stand initiation phase dominated by shrubs and saplings. Young stands represent the stem exclusion phase (post-canopy closure) and consist of young, dense forest with very low understory light levels. In mature stands, stem density has declined and canopy gaps result in increased light on the forest floor. With higher light levels, herb and shrub species become more abundant and a multi-layered canopy begins to develop. Late-seral stands are characterized by a complex canopy structure, large living trees, and large standing dead tress and downed logs.

To map current forest age, the Interagency Vegetation Mapping Project (IVMP, USDI and USDA, 2001a) "continuous quadratic mean diameter" data layer was used. This layer depicts mean diameter of dominant and codominant trees. The data are derived from a supervised classification of 1996 Thematic Mapper imagery (25 m resolution). This classification process used field data collected by the US Bureau of Land Management (Current Vegetation Survey) and USDA Forest Service (Forest Inventory Analysis) to model, test and assess accuracy (USDI and USDA, 2001b). The IVMP quadratic mean diameter values were compared with 144 plots of known age as determined by tree cores collected between 1998 and 2000. Linear regression was used to identify relationships between diameter and age and thus select minimum diameter thresholds for the mature and late-seral age classes; the regeneration and young classes were combined into one preliminary class. Change detection techniques (Lunetta and Elvidge, 1998) were then used to separate the regeneration and young classes, and update the map to 1998 (Fig. 3a). ARC/INFO (v. 7.1, ESRI) was used for change detection analyses and map production; ERDAS IMAGINE software (v. 8.5, ERDAS, Inc.) was used for all other analyses.

2.5. Management scenarios

The HARVEST model (Gustafson and Crow, 1999) was used to project the distribution of these four age classes 200 years into the future under three management scenarios. Because of the stochastic parameters within HARVEST, three replicates were generated for each scenario. Employing a 200-year simulation timeframe allowed the potential for all stands to reach the late-seral age class.

HARVEST is raster-based, simulation software designed to project landscape pattern under alternative timber management regimes (Gustafson and Crow, 1999). Four input maps were required for the simulation: initial stand age, stand boundaries, forest type, and ownership. The base map of current (1998) forest age was used as the initial stand age map for all simulations. The stand boundary map contains a unique identifier for each stand, which HARVEST uses to select stands for harvest. The forest-type data layer was used to designate the forest available for harvest, the non-forest areas (rivers, lakes, residential areas, municipal lands, and gravel pits), forest available for harvest, and reserve areas where harvest is not permitted. Because each management scenario has different requirements for reserve areas, each scenario required a separate forest-type layer. Data inputs entered in HARVEST (by land ownership) included mean harvest patch size, standard deviation in harvest patch size, harvest dispersal pattern, minimum harvest age, area harvested per 10-year step, and adjacency and green-up requirements (i.e., the prescribed height or age of adjacent stands before harvest is allowed). Stands are randomly selected for harvest from those stands meeting constraints of age and forest type. The size of each harvest patch is randomly drawn from the size distribution specified by the mean and standard deviation of harvest patch size. It was assumed that there would be no large natural disturbance during the study period.

The scenarios reflect the three proposed rule packages considered in detail by the Washington Forest Practices Board in the Final EIS (Table 1). ALT1 is the no action alternative, which would revert forest practices to the last set of permanent rules (November 1998). More restrictive Forests and Fish Emergency Rules in place since January 2000 would have been nullified if this option had been adopted. ALT2 reflects the recommendations of the Forests and Fish Report (Five Caucus, 1999) with some modifications and is the option that was ultimately adopted in July 2001 (thus superceding the Forests and Fish Emergency Rules). ALT3 is a compilation of proposals submitted by parties that opted out of the Forests and Fish process, including the Washington Environmental Council, Audubon Society, Muckleshoot Indian Tribe, Yakama Indian Nation, and Puyallup Indian Tribe (WFPB, 2001a). The primary difference among these alternatives is the degree of buffering of hydrological features and unstable slopes on private lands (Table 1).

Harvest practices for the models were drawn from current regulations and policies, including the Northwest Forest Plan, Washington's Habitat Conservation Plan, Washington Forest Practice Rules, Quinault Forest Practice Regulations, and land owner interviews carried out in 2001. Annual harvest goals and minimum harvest age were provided by each owner except those of private lands, where it was impractical to talk to every individual. Annual harvest area on private lands was estimated from the most current Washington Department of Natural Resources Timber Harvest Report available (1999) and was converted to area assuming 100 million (Scribner) board ft/ha based on empirical yield tables (assumes 16 foot logs, 80% stocking and 50-year site index of 100; WDNR, 1978).

2.6. Administratively withdrawn reserve areas

Federal, state and tribal regulations and policies were applied, which call for no-harvest buffers around streams, wetlands, unstable slopes, and areas occupied by spotted owls and marbled murrelets (Tables 1 and 2). Average buffer widths were used to model these scenarios (Tyler, 2002). In practice, many site-specific factors affect actual buffer width including site class,

Table 1
Summary of the differences between the three alternatives modeled (private lands only; simplified from WFPB, 2001a,b)[a]

Parameter	ALT1	ALT2	ALT3
Water typing system	Fish-bearing waters Type 1 = shorelines of the state Type 2 = generally >6 m wide Type 3 = generally <6 m wide Non-fish bearing waters Type 4 = generally >6 m wide Type 5 = generally <6 m wide Type 9 = unclassified	Fish habitat waters S = shorelines of state F = other fish habitat waters Non-fish habitat waters Np = perennial waters Ns = seasonal waters	Geomorphic-based system 0–20% slope 20–30% slope >30% slope
Riparian reserve widths (applied to each side of stream)	1 = 15 m 2 = 15 m 3 = 15 m 4 = 0 m 5 = 0 m 9 = 0 m	1 = 32 m 2 = 32 m 3 = 32 m 4 = 15 m half the length 5 = 0 m 9 = 0 m	<20% = 61 m 20–30% = 30 m >30% = 21 m
Wetland buffers			
Type A (>2 ha)	Type A = 30 m	Same as ALT1	Type A = 61 m
Type B (0.1–2 ha)	Type B = 15 m		Type B = 61 m
Unstable slopes	High-hazard slopes as identified by Washington Department of Natural Resources (WDNR) slope morphology model, SMORPH, but with areas <0.2 ha removed	Same as ALT1	All areas identified as high-hazard slopes by WDNR SMORPH model
Marbled murrelets	425 m radius circular buffer around all occupied sites	Same as ALT1	Same as ALT1
Northern spotted owls	All existing mature and late-seral forest within an owl circle in spotted owl special emphasis areas having less than 2374 ha of suitable habitat	Same as ALT1	Same as ALT1

[a] Under ALT1, Washington Forest Practice Rules classified streams as Type 1–5, based on fish presence and stream width. Under ALT2, the water typing system described is not yet in place. Washington Department of Natural Resources is in the process of updating their hydrological data to reflect the new system, however until that is complete, the interim system relies on the old typing system, whereby Type S = Type 1, Type F = Type 2 and Type 3, Type Np = Type 4, and Type Ns = Type 5. ALT3 used percent slope as the only criterion for classifying waterways. Each alternative specifies a range of buffer widths based on site-specific characteristics. The riparian reserve widths listed here reflect the average widths used in the model.

stream width, slope, wind susceptibility, status of adjacent lands, current stem density and basal area, and land owner preferences. As a result, some buffers in the field may be wider or narrower than the assumptions included in these scenarios. The landcover map was resampled to a 10 m cell size for buffering.

2.7. Landscape pattern analysis

Many indices exist to describe landscape pattern (Riiters et al., 1995; Gustafson, 1998), however many of these are redundant or are meaningful only at certain spatial scales (McGarigal and Marks, 1995; Riiters et al., 1995; Leitao and Ahern, 2002). Seven indices were selected that describe the amount and distribution of the late-seral forest category (Table 3). Percent of the landscape (%LAND) provides a basic summary of total available habitat. Core area percent of the landscape (C%LAND) provides a measure of interior habitat, which is a more relevant measure for species adversely affected by edge environments. Mean patch size (MPS) is arguably the most important

Table 2
Administratively withdrawn reserves by non-private owners[a]

	Olympic National Forest	Quinault Indian Nation	Washington Department of Natural Resources (WDNR)
Riparian buffer			
Type 1	91 m	30 m	55 m
Type 2	91 m	24 m	55 m
Type 3	91 m	24 m	40 m
Type 4	46 m	24 m	34 m
Type 5	43 m	0 m	0 m
Wetland buffer	46 m (wetlands >0.4 ha) 30 m (wetlands <0.4 ha)	30 m (wetlands >2 ha) 15 m (wetlands 0.1–2 ha)	43 m (wetlands >2 ha) 29 m (wetlands 0.1–2 ha)
Unstable slopes	Identified through watershed analysis	High-hazard slopes as identified by WDNR slope morphology model, SMORPH, but with areas <0.2 ha removed	All areas identified as high-hazard slopes by WDNR SMORPH model
Marbled murrelets	300 m radius circular buffer around occupied sites	Existing late-seral forest in the northern boundary portion of the Quinault Indian Nation Reservation will be retained	425 m radius circular buffer around occupied sites
Northern spotted owls	359 m radius circular buffer around nests or activity centers	Existing late-seral forest in the northern boundary portion of the reservation will be retained	>20% LPU >100 years, >20% LPU >70 years; LPU = landscape planning unit

[a] These represent average values included in the modeling exercise. Actual buffers in the field could be wider or narrower. Olympic National Forest provided digital files depicting all buffers for hydrological features and unstable slopes, based on watershed analysis. The buffer widths included for Olympic National Forest Plan here are drawn from the Northwest Forest Plan and are included for comparison with other land owners.

descriptor of the landscape (McGarigal and Marks, 1995); a reduction in MPS is included in many definitions of fragmentation (Andrén, 1994; McGarigal and Marks, 1995). Patch size coefficient of variation (PSCV) measures the variability in patch size as a percentage of the mean (McGarigal and Marks, 1995). Patch density, when considered in the context of percent of the landscape, gives a measure of the

Table 3
Landscape metrics included in the analysis[a]

Metric	Acronym	Description
% Landscape (%)	%LAND	Percentage of the landscape occupied by the late-seral age category
Core area percent of landscape (%)	C%LAND	Proportion of interior late-seral forest over the entire landscape. All areas greater than 100 m from the edge of another forest type were considered interior
Mean patch size (ha)	MPS	Mean size of all late-seral patches in the landscape
Patch size coefficient of variation	PSCV	Coefficient of variation in late-seral patch size
Patch density (number per 100 ha)	PD	Number of late-seral patches per 100 ha of the landscape
Contrast-weighted edge density (m/ha)	CWED	Sum of all edges per unit area of the landscape, adjusted by the degree of edge contrast. Contrast weight values range from 0 to 1, with 1 being maximum contrast. Maximum contrast edge (100 m/ha) will have a CWED of 100 m/ha. Low contrast (100 m/ha, 0.2) edge will have a CWED of 20 m/ha. The higher is the value, the greater is the amount of equivalent maximum contrast edge in the landscape
Mean nearest neighbor (m)	MNN	Sum of the nearest edge-to-edge distance between each late-seral patch, divided by the number of patches

[a] Descriptions of the metrics are based on McGarigal and Marks' (1995) discussion of category-scale metrics.

degree of habitat fragmentation. Contrast-weighted edge density characterizes the amount of edge in a landscape and the degree of contrast between edges. Microclimatic edge effects have been defined in this study as extending for 100 m from the forest edge. Mean nearest neighbor (MNN) quantifies the mean distance between patches, which is important for species interactions (Morrison et al., 1998), the ability of species to disperse between patches, and the extent to which metapopulations can be successfully maintained between subpopulations (Gilpin and Hanski, 1991). FRAGSTATS (McGarigal and Marks, 1995) was used for all spatial pattern analyses.

Analysis of variance (ANOVA) was used to test for significant differences among scenarios for the landscape metrics considered (Wear et al., 1996; Pearson et al., 1999). Significant ANOVA results were followed by multiple comparison tests using the Tukey method at an α-level of 0.05.

3. Results and discussion

3.1. Simulated future conditions

When looking at all owners combined, the differences between the present conditions and those of future alternatives are visually striking (Figs. 3 and 4). Late-seral forest increases roughly 5-fold in spatial extent and mature forest drops to less than half its previous extent (Table 4). Young forest, while still the dominant forest category, occupies 20% less of the landscape under future scenarios. Regeneration forest ranges between 10 and 15% of the area in future scenarios.

Table 4
Mean proportions of area in each forest-age category after 200 years (over all land owners combined)

Category	Present (%)	ALT1 (%)	ALT2 (%)	ALT3 (%)
Regeneration	14	11	10	9
Young	65	46	45	41
Mature	13	4	4	3
Late-seral	8	39	41	47

The degree of change in the distribution of age categories varies by land owner. Although area in late-seral forest increases across all land owners in the future, the biggest change is in the federal lands of the Olympic National Forest (Table 5). Washington Department of Natural Resources holds the next largest proportion of late-seral forest. In the current landscape, Washington Department of Natural Resources lands closely resemble private and tribal lands. In the future, Washington Department of Natural Resources lands will be more similar to federal lands (Table 5), and the proportion of late-seral forest will increase on private and tribal lands.

The differences in the landscape metrics among the three future alternatives result solely from patterns on private lands, because management practices were held constant on other ownerships during the simulations. All metrics describing the distribution of the late-seral forest category were significantly different

Table 5
Distribution of area in forest-age categories by owner[a]

	Olympic National Forest		Quinault Indian Nation		Washington Department of Natural Resources		Private			
	Present (%)	Future (%)	Present (%)	Future (%)	Present (%)	Future (%)	Present (%)	ALT1 (%)	ALT2 (%)	ALT3 (%)
Regeneration	8	<1	15	17	15	5	19	19	17	13
Young	44	1	77	67	67	41	73	67	62	42
Mature	24	1	7	3	11	8	7	5	4	3
Late-seral	24	98	1	13	7	46	1	9	17	42

[a] The three alternatives considered for the Washington Forest Practice Rules apply only to private lands. Future conditions for other ownerships were modeled under each alternative, however the input parameters for non-private lands were held constant across all three alternatives. Thus only the private ownership shows all three alternatives in this table. The "Future" conditions presented for other owners were taken from the ALT2 simulation. The age category proportions are essentially the same for all three alternatives (although the spatial configuration of each age category varies due to the stochastic nature of the HARVEST model). The percentages presented here are mean values of the three replicates generated for each scenario.

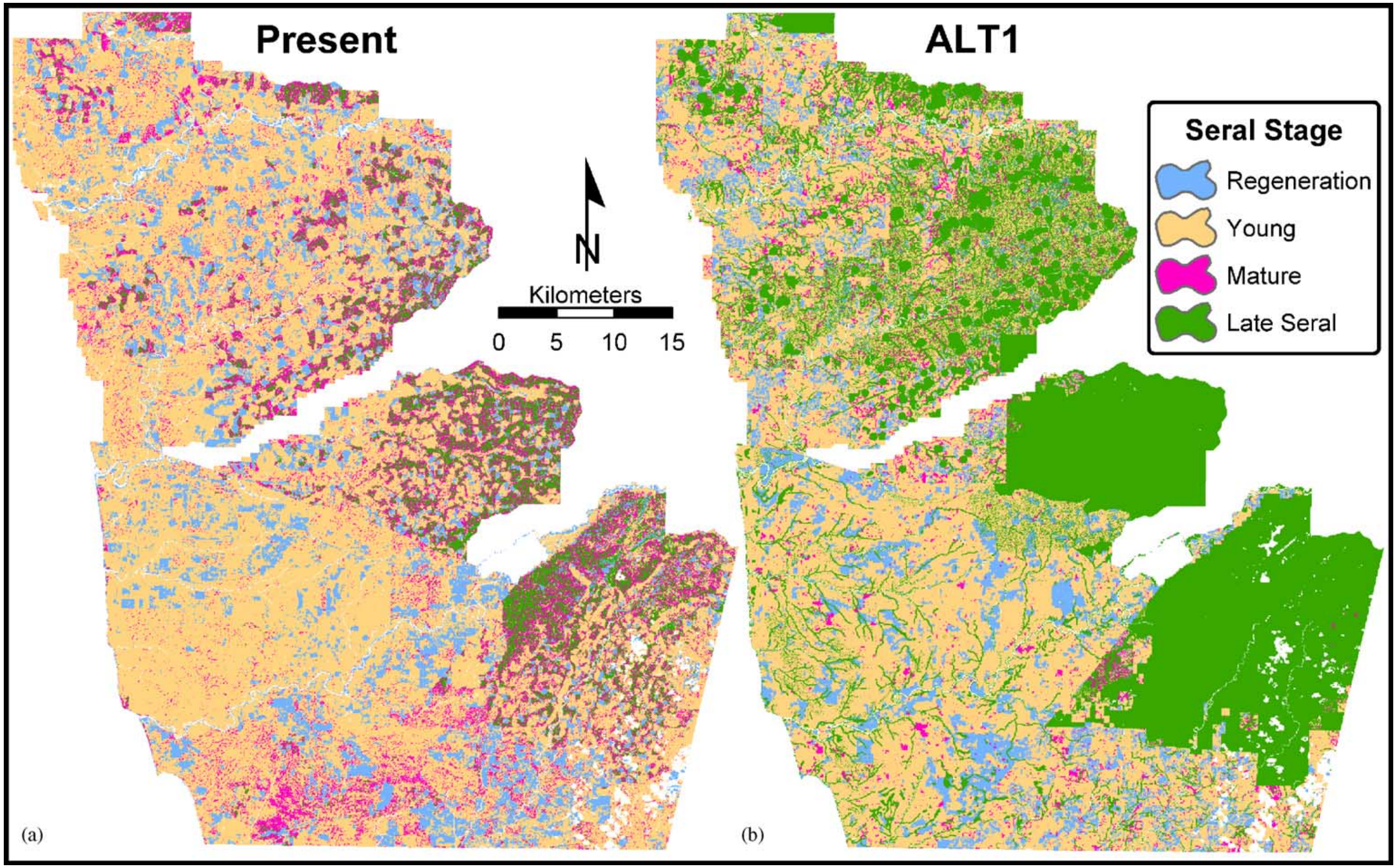

Fig. 3. (a) Present (1998) distribution of age classes on the Western Olympic Peninsula. (b) Future distribution of age classes under ALT1.

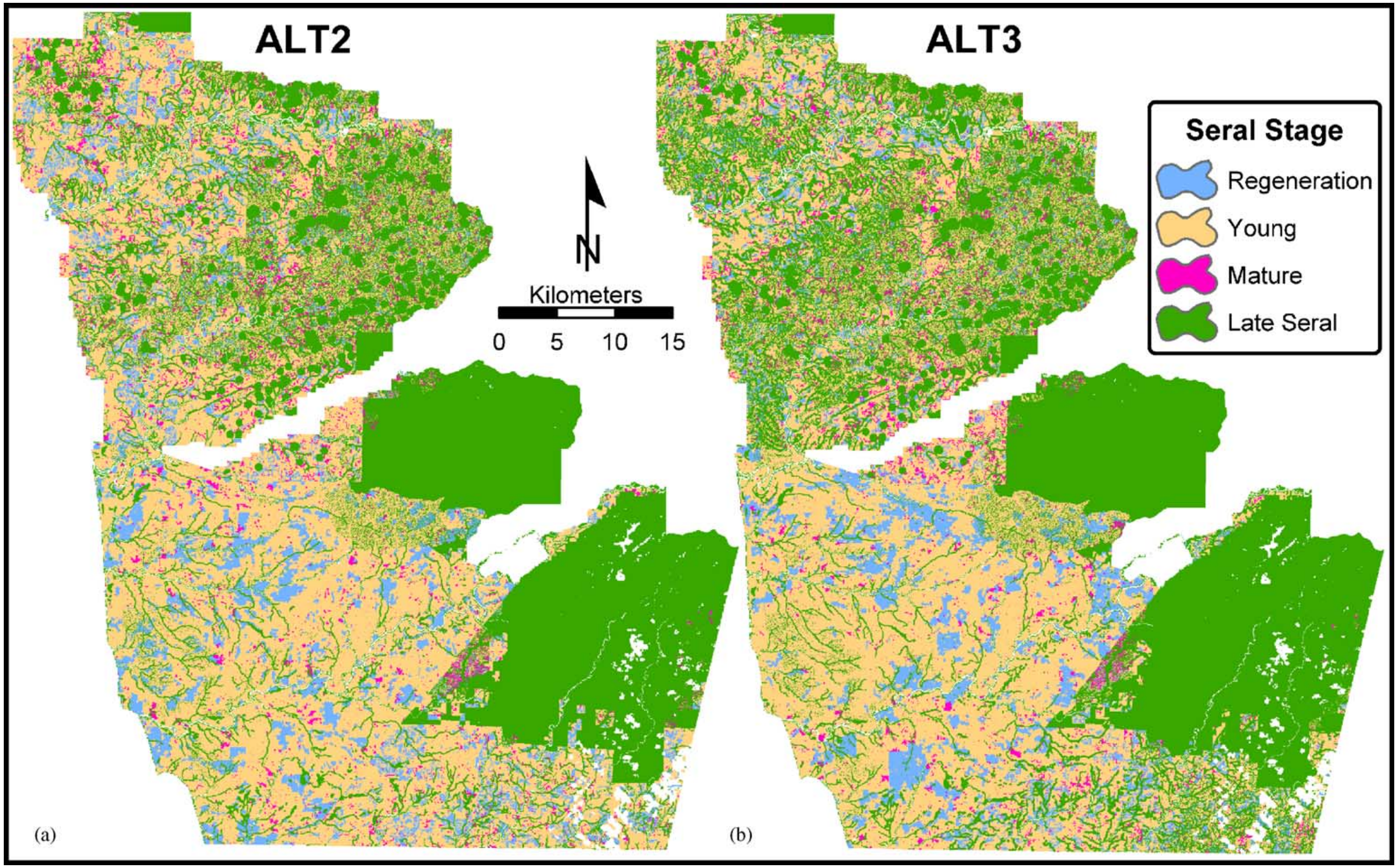

Fig. 4. Future distribution of age classes under (a) ALT2 and (b) ALT3.

Table 6
Mean and ranges ($n = 3$) of the landscape pattern indices for the late-seral class (present and future under three alternatives), and P-values derived from analysis of variance (ANOVA)[a]

Metric	Present	Alternative			P
Percent of landscape (%LAND)		ALT1	ALT2	ALT3	≪0.001
Mean	7.80	39.24	40.97	46.76	
Range		39.23–39.25	40.95–40.98	46.74–46.77	
Core area percent of landscape (C%LAND)		ALT2	ALT1	ALT3	≪0.001
Mean	0.03	21.54	21.55	22.21	
Range		21.52–21.55	21.52–21.57	22.21–22.22	
Mean patch size (MPS)		ALT1	ALT2	ALT3	≪0.001
Mean	1.64	5.01	5.07	6.20	
Range		5.01–5.03	5.69–5.71	6.19–6.20	
Patch size coefficient of variation (PSCV)		ALT2	ALT1	ALT3	0.01
Mean	1296	6174	6238	6544	
Range		6079–6341	6234–6246	6521–6589	
Patch density (PD)		ALT2	ALT3	ALT1	≪0.001
Mean	4.77	7.19	7.54	7.82	
Range		7.18–7.20	7.53–7.55	7.81–7.83	
Contrast-weighted edge density (CWED)		ALT1	ALT2	ALT3	≪0.001
Mean	4.3	23.6	24.3	28.7	
Range		23.1–23.9	23.6–24.6	28.3–29.0	
Mean nearest neighbor (MNN)		ALT3	ALT2	ALT1	
Mean	70.7	34.9	35.7	35.8	0.001
Range		34.8–35.0	35.7–35.8	35.6–35.9	

[a] Lines over text indicate alternatives that were not significantly different from one another as determined by the Tukey method.

among alternatives ($P < 0.001$), except for PSCV, which was significant at $P = 0.01$ (Table 6). In four of the seven metrics (core area percent of landscape, PSCV, contrast-weighted edge density, and MNN), ALT1 cannot be distinguished from ALT2. ALT3 can be distinguished from other scenarios in all metrics.

In the present landscape, interior late-seral forest occupies less than 1% of the landscape and increases to over 20% in future scenarios. Despite a significant difference between ALT1 and ALT2 in percent of the landscape (%LAND), there is no difference in the proportion of interior forest (C%LAND) between the two scenarios (Table 6). The proportion of suitable habitat in a landscape is generally considered to be more important than habitat configuration (Fahrig, 1997). However, as this proportion falls below a threshold, fragmentation may contribute to greater declines in number of species or population abundance than can be expected from habitat loss alone (Wilcove et al., 1986). Estimates for that threshold vary, from 10 to 30 (Andrén, 1994) to 30–50 (Flather and Bevers, 2002) to 60% (Pearson et al., 1996) of the landscape.

3.2. Interpreting landscape metrics

The landscape metrics paint a mixed picture of fragmentation under future alternatives: increased patch size and decreased MNN are indicative of enhanced connectivity and reduced fragmentation, however, increased contrast-weighted edge density suggests a more fragmented landscape. In landscapes having a similar proportion of suitable habitat, high patch density indicates greater fragmentation. MPS in the future alternatives is more than three times greater than present conditions, which would favor interior specialists that show strong effects of patch size (Bender et al., 1998; Connor et al., 2000). The similarity in MNN between ALT1 and ALT2 indicates that inter-patch distance is indistinguishable between these two alternatives. Under scenario ALT3, however, patches are significantly closer together than in the other scenarios. Differences in connectivity could become increasingly important as the total amount of habitat declines, particularly when total habitat drops below 25–30% (Bunnell et al., 1999). Due to varying dispersal abilities, connectivity is species-specific and therefore scale-specific (Wiens and Milne, 1989; Pearson et al., 1996). There is no discernible difference in the amount of contrast-weighted edge density between ALT1 and ALT2. ALT3 however has significantly higher edge density, which could negatively impact interior species. Generalists that occupy both edge and interior habitats are less impacted by fragmentation (Bender et al., 1998; Connor et al., 2000). ALT1 has the lowest %LAND and yet has the highest patch density, suggesting that ALT1 is more fragmented in late-seral forest than are ALT2 or ALT3.

High PSCV correlates to greater heterogeneity in patch size across the landscape. Bunnell et al. (1999) argue that increased heterogeneity better emulates natural disturbance processes and is vital for maintaining a heterogeneous and diverse ecosystem. Cissel et al. (1999) further this argument, suggesting that managing for historical conditions in landscape structure (which would include higher patch size variability than present conditions) would pose less risk to native species and ecological processes. There is no difference in PSCV between ALT1 and ALT2, however ALT3 has significantly higher variability (Table 6).

In summary, ALT1 and ALT2 are indistinguishable with respect to core area percent of landscape (C%LAND), PSCV, contrast-weighted edge density (CWED), and MNN. In contrast, ALT3 is significantly different from the other scenarios in all indices. Under ALT3, late-seral forest occupies a greater proportion of the landscape, has a larger patch size, and more interior forest area. Neighboring patches of late-seral forest are closer than under other scenarios, but the edge density is higher.

3.3. Ecological implications of the three alternatives

The implication of these results for obligate interior forest species is that the gains in late-seral forest under the recently adopted rules (ALT2) represent a small benefit over the no-action alternative of the 1998 rules (ALT1). ALT3 offers substantially more interior late-seral forest than the other two alternatives and connectivity is improved. However, because of the roughly linear nature of the riparian reserves, edge density is also significantly higher under this alternative. Interior obligates would benefit from the increased area and patch size of ALT3. However, there is a potential that these high-edge reserves could serve as population traps, attracting individuals to areas where they could face increased predation and parasitism.

The variation of these metrics among replicates is quite low (Table 6), contributing to the highly significant differences among alternatives. Given the regulatory requirements and management goals of various owners, late-seral forest occurs in nearly the same location in each replicate of a modeled scenario, and occupies 98% of the Olympic National Forest lands in the future. Natural disturbance was not modeled, and thus, large blocks of late-seral forest are essentially fixed by the simulations. Private and tribal lands managed for timber are generally logged on a 50-year rotation, thus these stands never approach the late-seral age category. Based on the harvest goals for these owners, late-seral forest seldom occurs outside those areas where harvest is prohibited by forest regulations (riparian buffers, unstable slopes, etc.).

Although these metrics show significant differences among scenarios, how different are these landscapes in an ecological context? For example, core area percent of landscape (C%LAND) is approximately 21.5% for ALT1 and ALT2, and 22.2% for ALT3. It is unlikely that there is a biologically meaningful difference in terms of core area. Modeling population viability of individual species or incorporating species dispersal capabilities and perception of landscape pattern would allow for an ecological interpretation that goes beyond quantification of differences in spatial patterning. Unfortunately, perception of landscape pattern remains unknown for most species. Use of pattern metrics will become more meaningful as this body of knowledge grows. In the interim, quantifying spatial pattern through landscape metrics may be the best tool for assessing suitability of habitat distribution for less studied or elusive species.

3.4. Factors potentially affecting results

The study boundaries selected for analysis affect the relative proportion and spatial pattern of age categories and thus the landscape metrics that describe them. To characterize the sensitivity of the analysis to varying study boundaries, a simulation was run under ALT2 model parameters that excluded the Olympic National Forest. When the simulation excluded the Olympic National Forest, late-seral forest occupied a smaller area and was more fragmented: percent of the landscape (25%) was lower, core area percent of landscape (3%) was much lower, MPS (3 ha) was lower, PSCV (5742) was lower, patch density (9/ha) was higher, contrast-weighted edge density (31 m/ha) was higher, and MNN (39 m) was higher than when the simulation included Olympic National Forest.

Under the spatial boundaries employed in this analysis, the proportion of late-seral forest under ALT2 is 41% for all lands, but only 9% on private lands (Table 4). Given the thresholds for minimum total habitat area that have been recognized (Wilcove et al., 1986; Andrén, 1994; Flather and Bevers, 2002), the configuration of habitat could be critical to success and persistence of species relying on late-seral habitat in landscapes dominated by private lands. Furthermore, the upper reaches of the study area include unstable slopes and a dense stream network; no-cut buffers around these areas will result in increased proportions of late-seral forest. Private lands that have lower stream density and level topography can be expected to have a lower proportion of late-seral forest.

Historic disturbance regimes were not incorporated into the simulation exercise. Including stochastic disturbance in the model would result in greater variability among replicates and a landscape more reflective of naturally occurring variation in age class extent and distribution. Wimberly et al. (2000) modeled historic variability in the proportion of old growth forest in the Oregon Coast Range and concluded that historical age-class distribution was highly variable. They projected a range of historic variability in natural disturbance regimes over a 3000-year period. They found that the percentage of old growth in the landscape ranged from 25 to 75%. The proportion of late-seral forest observed today in the Olympic National Park (44%) is similar to estimates of old growth forest in western Oregon in the late 19th century (Teensma et al., 1991; Ripple, 1994).

Natural disturbances affecting this landscape vary temporally and spatially. Canopy gaps, bank erosion, river meanders, and landslides typically occur frequently and are small (0.05–5 ha). Fires occur less frequently (fire return interval of the Sitka spruce zone is estimated at 900 years) and are seldom larger than 400 ha (Henderson et al., 1989). The 1921 windstorm affected 1.2 million ha, but much smaller cyclonic wind events have occurred 10 times in the last 200 years (Henderson et al., 1989). Climatic variability could leave a legacy lasting millennia, covering an area far greater than the study area. Natural disturbances are the source of age class variation within the park, which includes 6% regeneration forest, 22% young forest, and 28% mature forest. The distribution of regeneration and young forests within the park is largely associated with river valleys and unstable slopes (and portions of the Queets River corridor, which were commercially logged prior to being added to the park in 1940).

Excluding disturbance from the model results in elevated amounts of late-seral forest in simulated landscapes. In particular, the large blocks of contiguous late-seral forest on Olympic National Forest lands may not be representative of the distribution of late-seral forest in a naturally occurring landscape. It is reasonable to assume that left undisturbed over time, these lands would be similar in age-class distribution to the Olympic National Park (i.e., interspersed with younger categories resulting from natural disturbance). For this reason, the age-class distributions in the future scenarios are most appropriately used for comparative purposes among scenarios, and some caution should be exercised when comparing these values in an absolute sense to landscapes affected by disturbance.

3.5. Impacts on mature forest

Although this discussion has focused on the late-seral category, distribution of mature forest is also worth noting. Mature forest is substantially reduced under the future scenarios because of the rotation ages used in timber-managed lands and the proliferation of late-seral forest in the reserves. Future landscapes contain 3–4% mature forest, in contrast to 13% in the present landscape (outside Olympic National Park) and 28% currently in Olympic National Park (Table 4). Cissel et al. (1999) predicted a similar result for mature forest in their study modeling implementation of the Northwest Forest Plan on federal lands in Oregon. As mentioned above, the proportion of mature forest could be expected to be higher if natural disturbance was incorporated in the model (particularly in the Olympic National Forest). However, this would be limited in timber-managed portions of the landscape. Increases in mature forest would be associated with decreases in late-seral forest. Limited spatial extent of mature forest could prove detrimental for species that reach the greatest abundance in this age class. Spies (1991) found that several understory herbs reached the highest percent cover (e.g., *Adenocaulon bicolor*, *Anemone lyallii*, *Arenaria macrophylla*, *Fragaria vesca*) and constancy (e.g., *A. macrophylla*, *Galium triflorum*, *Holodiscus discolor*, *Pyrola picta*, *Senecio bolanderi*, *Vancouveria hexandra*) in mature forests of Washington and Oregon. Spies (1991) also found that bigleaf maple (*Acer macrophyllum*) achieved the greatest basal area and grand fir (*Abies grandis*) had the highest constancy in mature forests. Alaback (1982) observed that bryophyte biomass peaked in mature forests of southeast Alaska.

4. Implications for future forest policy

Forest policy has tremendous ramifications for natural systems, because of the spatial scale at which it is implemented and the persistence of the resulting landscape structure. Simply managing for total amount of habitat will not necessarily be sufficient for assuring the persistence of species; spatial arrangement of habitat becomes critical as availability of habitat declines (Wilcove et al., 1986; Andrén, 1994; Flather and Bevers, 2002). Single-ownership, small-scale policies that are not based in ecologically meaningful boundaries will be impractical, inefficient, and ineffective in managing for large-scale patterns and processes. The cumulative effects of negative impacts at multiple scales can be seen in the case of declining salmon (*Oncorhynchus* spp.) in the Pacific Northwest, which spurred the recent revisions to the Washington Forest Practice Rules. Human activities have adversely affected salmon at a variety of scales (both spatial and temporal), and a multi-scale solution will be required for restoration of salmon habitat (Peterson and Parker, 1998).

The most successful forest policies will be proactive and comprehensive, and will address ecological relationships at multiple scales. Reactive strategies developed in response to crises are more likely to overlook important relationships and manage resources inefficiently (i.e., fine-filter restoration is more difficult and expensive than prevention). For example, management strategies aimed at a few species or ecosystem functions may enhance viability for one group of species or processes at the expense of others. Similarly, managing activities at a fine scale (using fixed buffers to manage for individual species) and ignoring coarse-scale dynamics (e.g., fragmentation, multiple species' impacts) may undermine management objectives by disrupting natural processes such as disturbance (Agee, 1999). Policy developers should evaluate how alternative policies affect diverse species and guilds, as well as considering impacts on ecological function at multiple scales. The narrow focus on aquatic species in the current policy has the potential to negatively impact interior forest species that are sensitive to fragmentation.

5. Conclusions

With the use of coarse-scale modeling tools, this analysis quantified impacts of alternative forest management policies on the amount and distribution of late-seral forest. Landscape metrics were used to quantify differences between simulated future conditions. In terms of late-seral forest, the alternative that was ultimately adopted as the Washington State Forest Practice Rules was indistinguishable from the no-action alternative in four of the seven metrics evaluated. A third alternative, which was proposed by a collection of environmental organizations and tribes, resulted in significantly more interior late-seral forest than the other two scenarios, but also resulted in significantly higher edge density, an important indicator of fragmentation.

The approach used in this analysis provides a framework for landscape pattern analysis for comparing three forest policy options. This straightforward approach is a useful tool for comparing alternative management scenarios. It can also be used to monitor progress towards stated landscape goals over time. Environmental impact assessment of land use policies with broad geographic impacts should include landscape pattern analysis. Much work remains to be done to understand species response to landscape structure, corridor use and design, dispersal capabilities in fragmented landscapes, the role of remnant patches in preserving plant and animal populations, and the relationship between landscape matrix and patch isolation. A greater body of scientific literature in these areas will enhance our understanding of the role of landscape pattern in ecological systems. Enhanced understanding of relationships between landscape structure and ecological function will allow for more robust analysis of alternative management scenarios and interpretation of landscape metrics (Bradshaw, 1998).

Finally, in the spirit of adaptive management, we must respond to surprises encountered along the way. Large-scale planning should reflect our best understanding of complex relationships (ecological and social) in light of many uncertainties. We face not only gaps in knowledge but also stochastic processes in natural systems, including disturbance. Our planning efforts therefore must be flexible and able to respond to changing trends and shifting critical targets.

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